[0120] A differential actuator represented by the impedance diagram of FIG. **8** behaves similarly to two electrical transformers connected in parallel with transducers T**1** and T**2**, having respectively two equivalent mechanical impedances $Z_1$ and $Z_2$. Then, the total equivalent mechanical impedance $Z_{eq}$ of the actuator of FIG. **8** seen from a load point of view is given by:

$$Z_{eq}=Z_1\frac{K^2}{(K+1)^2}//Z_2K^2=\frac{Z_1Z_2K^2}{(K+1)^2Z_2+Z_1}$$

[0121] As indicated in the foregoing description, a high performance differential actuator is characterized by the following relation:

$$(K+1)^2Z_2>>Z_1.$$

[0122] Accordingly, the impedance $Z_{eq}$ can be approximated by:

$$Z_{eq}\cong\frac{K^2}{(K+1)^2}\cdot Z_1.$$

[0123] Therefore, a property of a differential actuator according to the illustrative embodiment of FIG. **8** is that there is a precise known relationship between the mechanical impedance $Z_{eq}$ of the differential actuator and the mechanical impedance $Z_1$ of transducer T**1**. The mechanical impedance $Z_2$ of transducer T**2**, which is in general very difficult to model, does not influence the mechanical impedance $Z_{eq}$ of the differential actuator. As a result, an interaction control between the differential actuator and the load **803** can be performed solely with impedance and/or force/torque control of transducer T**1**. The aforementioned four categories of differential actuators provide four different examples as to implementing interaction control, i.e. force/torque and/or constant/variable impedance interaction control.

[0124] Advantages of Differential Actuation

[0125] Differentially coupling two transducers is quasi equivalent to serial coupling when computing the impedance seen from the load. In a "force/tension" impedance diagram of a "serial impedance actuator" as illustrated in FIG. **13**, transducers T**1** and T**2** are connected in parallel.

[0126] Different categories of "serial impedance actuators" have been proposed in the patent literature, for example in references [9] and [10]. Several particular implementations are described and claimed, in particular linear serial elastic actuators.

[0127] Differential coupling offer implementation advantages compared with serial coupling. In particular, high performance rotational actuators are best implemented using a differential coupling between transducers T**1** and T**2** than using a serial coupling. An additional advantage, amongst others, comprises a more compact and simpler design as demonstrated by the examples of implementation described in the following description.

Physical Implementations

[0128] Implementations of a Mechanical Differential

[0129] Any speed reduction mechanism can be used to implement the mechanical speed reducer(s) of a mechanical differential actuator according to the present invention. Examples of speed reduction mechanisms comprise, amongst others, standard gearboxes, cycloidal gearboxes, bar mechanisms, cable mechanisms, and any other mechanism capable of implementing the mechanical function of speed reducer. The difference between a speed reducer and a mechanical differential can be understood by looking at what is connected to the three mechanical ports of the differential actuator. The two simple bar mechanisms of FIGS. **14** and **15** can be used to illustrate this conceptual difference.

[0130] FIG. **14** shows a mechanical speed reducer comprising 3 mechanical ports respectively connected to an input transducer $O_1$, a fixed chassis $O_2$ and a load $O_3$.

[0131] In contrast, FIG. **15** illustrates a differential actuator according to an illustrative embodiment of the present invention, comprising 3 mechanical ports respectively connected to transducer T**1** ($O_1$), transducer T**2** ($O_2$) and a load $O_3$.

[0132] Use of a harmonic drive technology to implement a differential mechanical function of a rotational differential actuator provides a very compact and simple design. As can be seen from FIG. **16**, the 3 building components of a harmonic drive, i.e. the wave generator WG, the flexible spline FS and the circular spline CS, can be bought separately from the company Harmonic Drive LLC, Peabody, USA. This hollow shaft system allows for the implementation of at least 3 different possible embodiments of rotational differential actuators according to the present invention.

[0133] More specifically, a harmonic drive may be viewed as a mechanical differential including 3 ports, namely its three building components WG, FS and CS. Since the operation of a harmonic drive is believed to be well known to those of ordinary skill in the art and that such drive systems are readily available on the market, the harmonic drive and its principle of operation will not be further discussed in the present specification.

[0134] The at least 3 possible implementations of rotational differential actuators according to illustrative embodiments the present invention and using the harmonic drive of FIG. **16** will now be described with reference to FIGS. **17***a*, **17***b* and **17***c*.

[0135] In the 3 implementations of FIGS. **17***a*-**17***c*, transducer T**1** is respectively a torsion spring **1702**, a constant/variable rotational damper **1703** and a limited angle torque motor **1704**. Transducer T**2** is a rotational direct drive brushless motor in the 3 cases. A non-rotating sensor C measures the torque output of the mechanical differential actuator.

[0136] Implementation 1

[0137] FIG. **17***a* illustrates a first possible design of rotational differential actuator using a hollow shaft harmonic drive as illustrated in FIG. **16** wherein transducer T**1** is a torsion spring **1702**.

[0138] In FIG. **17***a*, transducer **72** comprises a rotor R connected to the wave generator WG of the harmonic drive.